Vernal Circulation Patterns and Processes in Penobscot Bay:

Preliminary Interpretation of Data

A Final Report for Year 2 of the Penobscot Bay Experiment

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INTRODUCTION:

Penobscot Bay is a large oceanographically-complex embayment at the mouth of the Penobscot River, which is one of the three most significant fresh water point sources for the entire Gulf of Maine. The two-way exchange between the bay and the Gulf is expected to play an important role in the ecosystem of each, through the interplay of their circulation systems and the exchange of nutrients and planktonic communities.

There is growing evidence that the circulation of Penobscot Bay and the eastern Maine shelf are strongly coupled. It is often suggested that the outflow from Penobscot Bay exerts an important influence on the general circulation of the Gulf of Maine by causing a portion of the generally southwestward-flowing Eastern Maine Coastal Current (EMCC) to be deflected offshore and to recirculate cyclonically (anticlockwise) within the Jordan Basin Gyre (e.g., Brooks, 1994; Lynch et al., 1997; Pettigrew et al., 1998). However, there may also be instances in which a buoyant estuarine plume emanating from Penobscot Bay overrides the coastal current without any apparent deflecting influence (Pettigrew et al., 1998). In addition, sea surface temperature (SST) patterns, as seen most clearly in Landsat images, sometimes indicate cold coastal-current waters entering the outer bay. The first direct evidence of strong physical coupling between the bay and the EMCC came from year one of the PenBay experiment. In the spring and summer of 1998, moored current measurements showed an unexpected pattern of strong near-surface and mid water column inflow in western Penobscot Bay, and net outflow in eastern Penobscot Bay. This striking circulation pattern suggested that the interactions between the bay and the EMCC dominated the summer circulation in the outer bay. The net inflow and outflow transports respectively on the western and eastern sides of Vinalhaven Island suggested an anticyclonic circulation pattern that was referred to as the Island Gyre. While these results were very exciting, we still had little idea of the circulation during the fall/winter period, the time variability of hydrographic and currents in the upper 10 m of the water column, and no direct knowledge of the circulation in the upper reaches of the bay.

OBJECTIVES OF THE SECOND YEAR OF THE CIRCULATION EXPERIMENT:

The primary objectives of the second year of the study were to verify the spring/summer circulation patterns observed in year one of the project, and to begin to characterize the main features of the subtidal (residual) circulation pattern in outer Penobscot Bay during the fall/winter period of 1998-99.

Specific experimental tasks for the project are listed below in descending order of priority:

- obtain direct current measurements at strategically sited (hopefully) mooring locations in the outer bay and the EMCC;

- obtain moored time-series record of water properties (temperature, salinity, and density) at the mooring sites, including measurements at 1m depth;

- obtain spatial current surveys, which if successfully detided, could provide a geographical context for the moored current measurements.

The data acquisition tasks listed above were successfully completed.

PRELIMINARY INTERPRETATION OF DATA:

Standard calibration and data processing techniques have been applied to the moored time series and hydrographic survey data collected during 1998. The details of the experimental sampling scheme, and the calibration and the processing routines used, are discussed in the companion data reports by Wallinga *et al*. (1999a,b). Plots of all hydrographic survey data and of all moored time-series data may also to be found in the data report. The data presented herein are only those required to illustrate the basic findings and to support the data interpretation and synopsis. Figure 1 shows the locations of the moorings and the hydrographic stations.

Hydrographic Surveys:

Three hydrographic/Doppler surveys of Penobscot Bay were conducted in connection with the 1998 circulation study. The dates of these surveys were April 27-30, Sept. 11-13, and Sept 30, 1998. The time series of Penobscot River fresh water discharge for the 1998 is shown in Figure 2. The April survey period occurred during the high runoff period (>1000 m^3s^{-1}) while the September cruises occurred during the low runoff season with discharge rates of approximately 200 m^3s^{-1}

In contrast to year one of the experiment, the hydrographic effort was concentrated on tidally average sections corresponding to the mooring locations in outer Penobscot Bay. The purpose of the surveys was to attempt to confirm that the inflows and outflow of the observed by the moorings were in fact representative of the conditions across the channel, and to help trace water masses associated with the transport. As shown in Figures 3-6, the tidal surveys confirmed the net inflow in the western side of the bay and net outflow on the eastern side. In addition, the tidally averaged salinity sections showed that the freshest waters were found in the upper water column of the western section indicating that the influence of the Penobscot River flow was principally manifest in the western bay. The peculiar pattern observed in the west is that the deep salty water is flowing out of the bay rather than into the bay, giving that section a "reverse estuarine" character. Paradoxically, the eastern bay has a more classical estuarine character with outflow of fresher waters and deep inflow of salty water, although as noted above, the river water is substantially isolated from the eastern bay.

Moored Time-Series Data:

Acoustic Doppler current measurements made at the western mooring site in Penobscot Bay are shown in Figure 7. The data represent 4 m vertical averages centered on the indicated depths. For clarity of presentation, only every third depth bin has been plotted. The data have been filtered to remove tides and higher frequency oscillations, and are presented as time series "vector stick plots". The directional convention is that the north/south component is plotted along the ordinate with northward being positive, and the east/west component of each vector is plotted from its time origin along the abscissa with eastward being positive. The speed, in cm s^{-1} is indicated by the length of the vector and may be measured against the scale on the ordinate. No reliable measurements were obtained shallower than 8 m or deeper than 92 m due to acoustic contamination associated with side-lobe reflections (Pettigrew and Irish, 1983).

The vertical and temporal structure of the residual currents shown in Figure 7 is surprising and complex. There is a clear qualitative difference between the flow structure May through late September, and the structure thereafter. During the May-September period the mean flow is northward at all depths down to 70 m, with strong northward (inward) flow in the upper 50 m. Currents below 78 m were net southward with steady outflow at 90 meters. This pattern is similar to that observed during the summer of 1997 and once again clearly shows a net inward transport of the order of 10^4 m^3s^{-1}.

Beginning in late September the character of currents changed dramatically to strongly southward in the upper 20 m with inflow below. The most dramatic changes occurred in the deep water where flows below 50 m became very strong with a mid-water maximum at about 70 m. This striking seasonal reversal in circulation resulted in fall/winter outflow at the surface and inflow at the bottom. Paradoxically, the switch to a more typical estuarine vertical current profile occurred during the low runoff period.

The general character of the currents at the shallower (60 m) east bay mooring, in 1997 were strikingly different from those observed at the west bay mooring. The upper layer currents (8m to 26 m) were remarkably constant and steadily southward except for two clearly wind-driven events. At depths of 34 m and deeper, in the 60 m deep water column, the currents reverse and flow northward into the bay. The currents were generally weaker and less variable than the west bay currents, and they showed no evidence of a flow transition between the March/April and May-July periods that was observed in the west bay.

In 1998, due to a malfunction of the Doppler profiler, currents in the east bay were only obtained for the upper layer (Figure 8). However, the currents that were measured were consistent with the near-surface currents observed in 1997; that is, steadily southward at approximately 15-20 cm s^{-1}. The most striking contrast with the western current records is the lack of variability at all subtidal time scales. The striking seasonal transition observed in the western bay is notably absent in the east. We assume that, as in 1997 moored records and as in our shipboard surveys, the deeper flow was inward throughout the experimental period.

Figure 9 shows vector stick plots of velocity measured at the inner mooring in the EMCC (Figure 1). These records represent the longest records to date of currents in the EMCC, and the first ever during the fall season. The directional convention is that the alongshelf component is plotted along the ordinate with northeastward being positive, and the cross-shelf component of each vector is plotted from its time origin along the abscissa with onshelf being positive. The speed, in cm s^{-1} is indicated by the length of the vector and may be measured against the scale on the ordinate. The plot shows that the flow is consistently alongshelf toward the southwest as is common in the EMCC with peak subtidal flows on the order of 35 cm s^{-1} .The time variability of the EMCC is intermediate between that of the high variability of the inflow region of western Penobscot Bay, and the low variability of the eastern bay, with no overall correlation to the wind stress shown in the top panel. The exceptions to the low wind correlation are two wind-driven events; one at the beginning of the record in May, and the other in early October. There is the appearance of a transition in the character of the EMCC in the early fall, but this change is principally due to the strong wind event rather than a seasonal transition as was observed in western Penobscot Bay (late September). This lack of correlation between the EMCC currents and those in western Penobscot Bay weaken the hypothesis that the anomalous flow conditions in the outer bay are due directly to inflow from the EMCC. It may be that variability in the western bay is a complex interaction between river inflow, wind forcing, and the local topography.

Figures 10 and 11 show the lowpass-filtered time series records of temperature salinity and density from the two Penobscot Bay moorings. The data were filtered with the PL33 filter to remove tidal and higher frequency fluctuations. The records at all depths show a seasonal cycle. The western Pen Bay salinity time series at 1 m depth shows large subtidal variations (order 5 ppt) that are more energetic than the seasonal fluctuations. The 1 m record from eastern Pen Bay shows higher salinity and lower fluctuations (order 1 ppt), reinforcing the notion that the Penobscot outflow is a much more important influence in the western portion of the bay. It is notable and regrettable that the density time series do not always show a stably stratified water column. This is undoubtedly an artifact reflecting the need for sensor servicing and recalibration. This problem will be addressed in year three with a combination of field and factory calibration..

FUTURE WORK:

A great deal of additional analysis and field measurements need to be performed before we can have confidence in any of the interpretations presented above. Many of our assumptions need to be tested, we need to obtain current measurements closer to the sea surface, and the gyre-like circulation needs to be more directly observed. Of even greater significance will be gaining direct measurements of the currents in the upper reaches of the bay. As of now we still know virtually nothing about the circulation in the upper bay. We speculate that it may be more influenced by the riverine inflow and less influenced by the EMCC, and thus behave more like a partially mixed estuary.

In the third year of our experimental effort we will be refitting the buoys with *in situ* acoustic current meters that can measure the near-surface flows that are of paramount importance in understanding dynamics of the bay's circulation, and its operation as an ecosystem. The near-surface currents will be especially valuable to colleagues studying the distribution and movements of larvae within the bay, and the relationship of currents to surface patterns of temperature and ocean color. This change will also greatly enhance our ability to evaluate the temporal variations in the influence of the Penobscot River on circulation and exchange.

A major shift in our spatial surveys is to shift our focus to across-channel tidal transects in the upper bay. We hope to add transects on either side of Islesboro Island and between Islesboro and North Haven. The hydrographic surveys can be repeated over a tidal cycle so that the tidal fluctuations and be averaged out and the residual hydrographic and current fields can be calculated. The goal of this facet of the work is to attempt to tie circulation in the upper bay to that in the lower bay.

SUMMARY AND CONCLUSIONS:

I. There is a strong seasonal transition in the current field west of Vinalhaven Island in Penobscot Bay. In the early fall, the current regime changes from the spring/summer pattern observed in both 1997 and 1998 to one characterized by surface outflow and inflow at depth. This seasonal transition is not clearly reflected in the flow in the EMCC. In each seasonal regime there is net inflow on the western side of the bay.

II. The current regime east of Vinalhaven Island is steadily outward in the upper water column, with no evidence of significant seasonal variability. The preponderance of evidence suggests that the net inflow of the western bay is balanced by a net outflow in the eastern bay. However, the lack of temporal correlation between the east and west is troubling, and suggests a more complex relationship than a simple through flow associated with a coherent gyre. It may suggest a more torturous pathway through the bay combined with vigorous vertical mixing.

III. The freshening influence of the Penobscot River observed during the spring is clear only on the western side of the bay. The lack of surface freshening on the eastern side could be a signature of isolation or intense vertical mixing of the waters as they pass through the shoal island archipelago separating the upper bay from the lower eastern bay.

References:

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Lynch, D.R., M.J. Holbrook, and C.E. Naimie, 1997. Dynamical influences on the Maine coastal current. Cont. Shelf Res.

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Pettigrew, N.R., D.W. Townsend, H. Xue, J. P. Wallinga, P. J. Brickley, and R. D. Hetland, 1998. Observations of the Eastern Maine Coastal Current and its Offshore Extensions in 1994. *Journal of Geophysical Research,* 103, C13, 30,623-30,639.

Wallinga, J., B. Wallinga, R. Stessel, L. Mangum, and N. Pettigrew, 1999a. The Penobscot Bay Experiment: Hydrography and Current Survey April 27-30, 1998.

Wallinga, J., B. Wallinga, R. Stessel, L. Mangum, and N. Pettigrew, 1999b. The Penobscot Bay Experiment: Hydrography and Current Survey September 11-13 & 29, 1998.

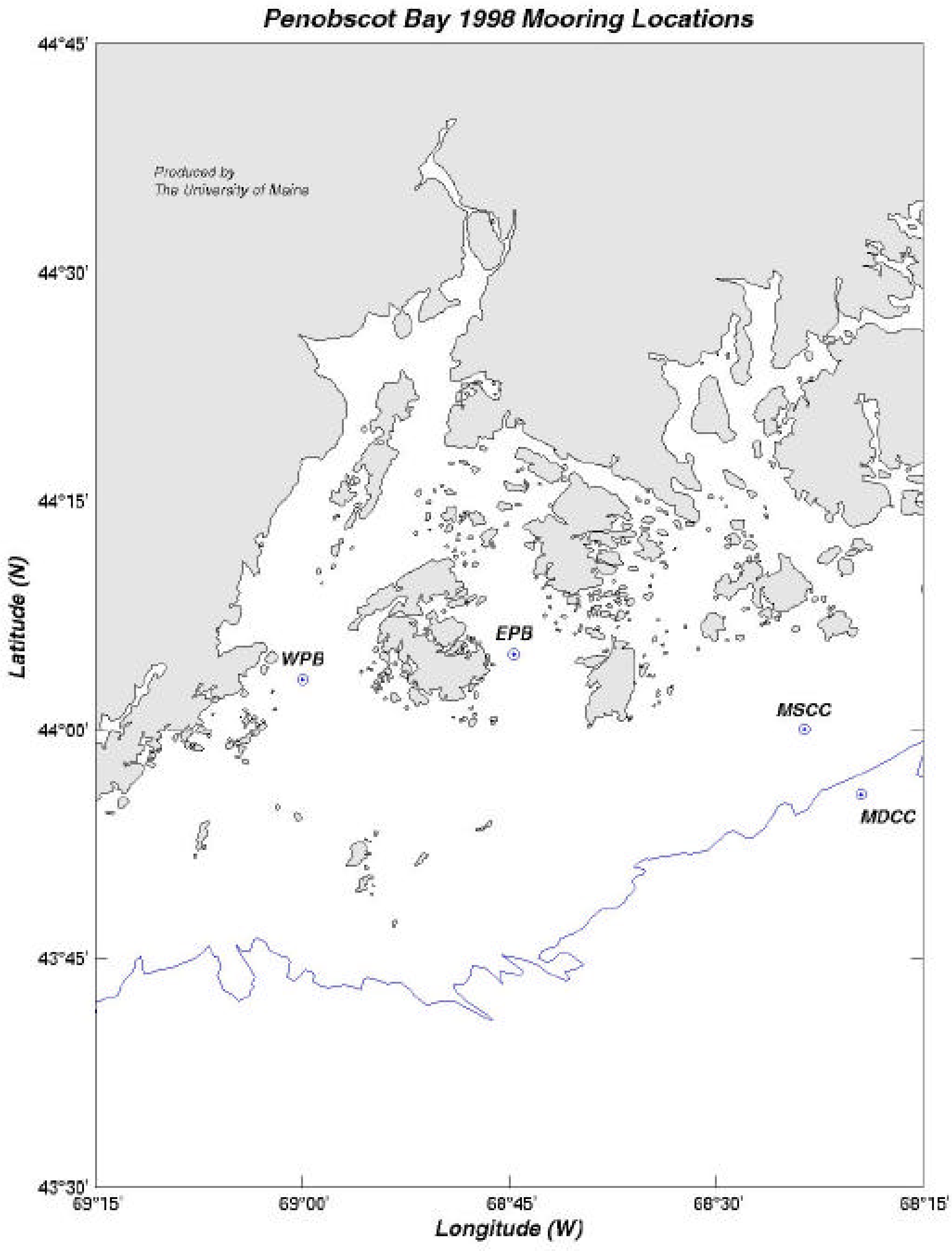
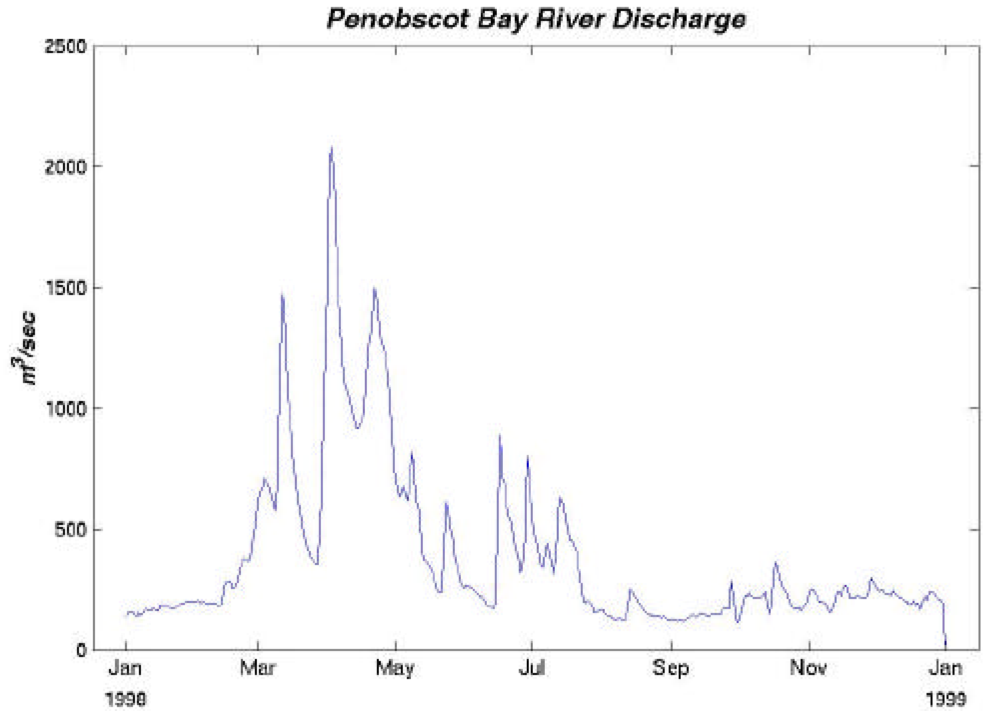

Penobscot Bay 1998 Mooring Locations
Produced by
The University of Maine
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
69°15'
69°00'
68°45'
68°30'
68°15'
Latitude (N)
Longitude (W)
WPB
EPB
MSCC
MDCC

Figure 1.


Penobscot Bay River Discharge
2500
2000
1500
1000
500
0
m^3/sec
Jan
1998
Mar
May
Jul
Sep
Nov
Jan
1999
Figure 2.

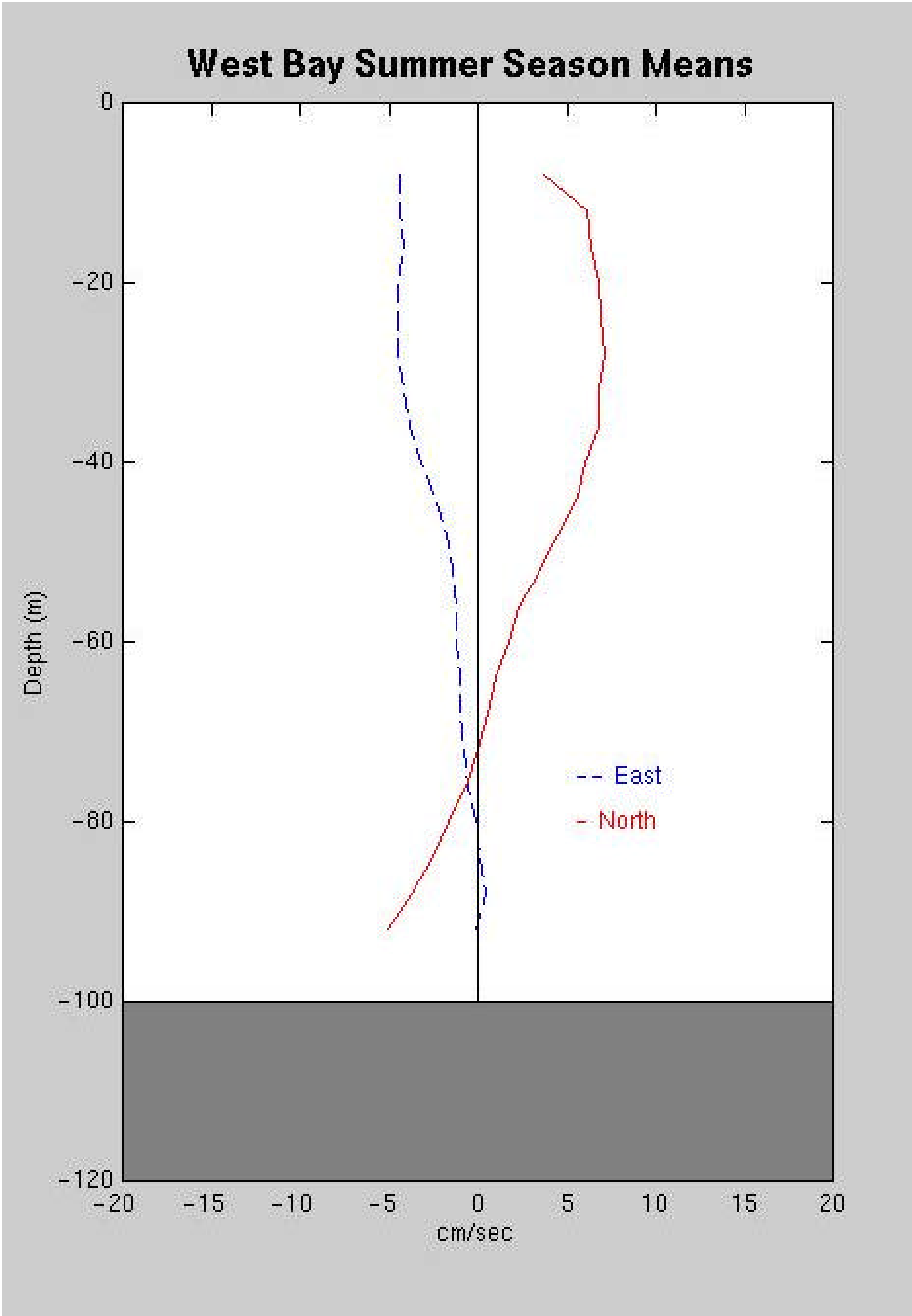

West Bay Summer Season Means
0
-20
-40
-60
-80
-100
-120
Depth (m)
-20
-15
-10
-5
0
5
10
15
20
cm/sec
-- East
- North

Figure 3.

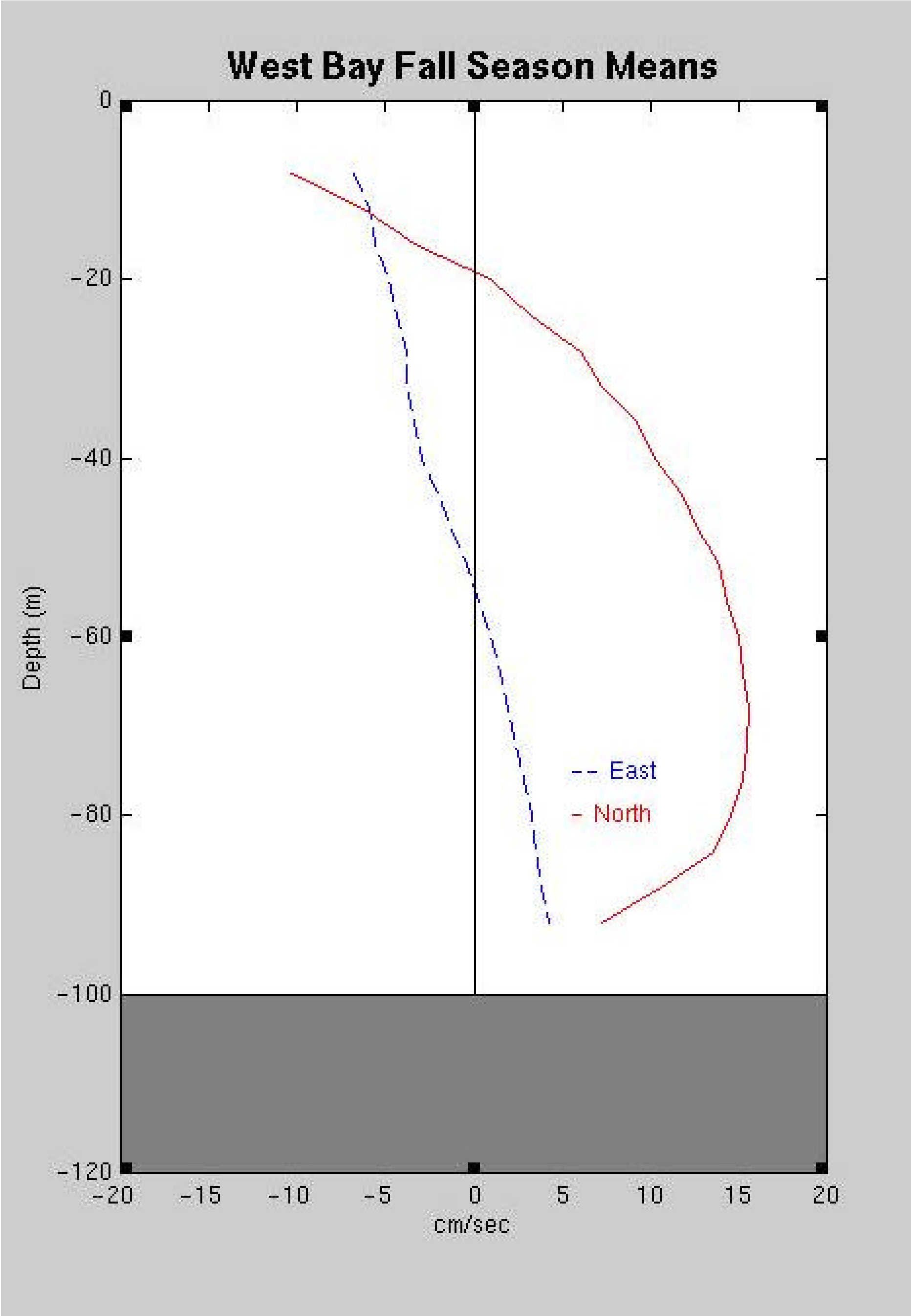

West Bay Fall Season Means
0
-20
-40
-60
-80
-100
-120
Depth (m)
-20
-15
-10
-5
0
5
10
15
20
cm/sec
East
North

Figure 4.

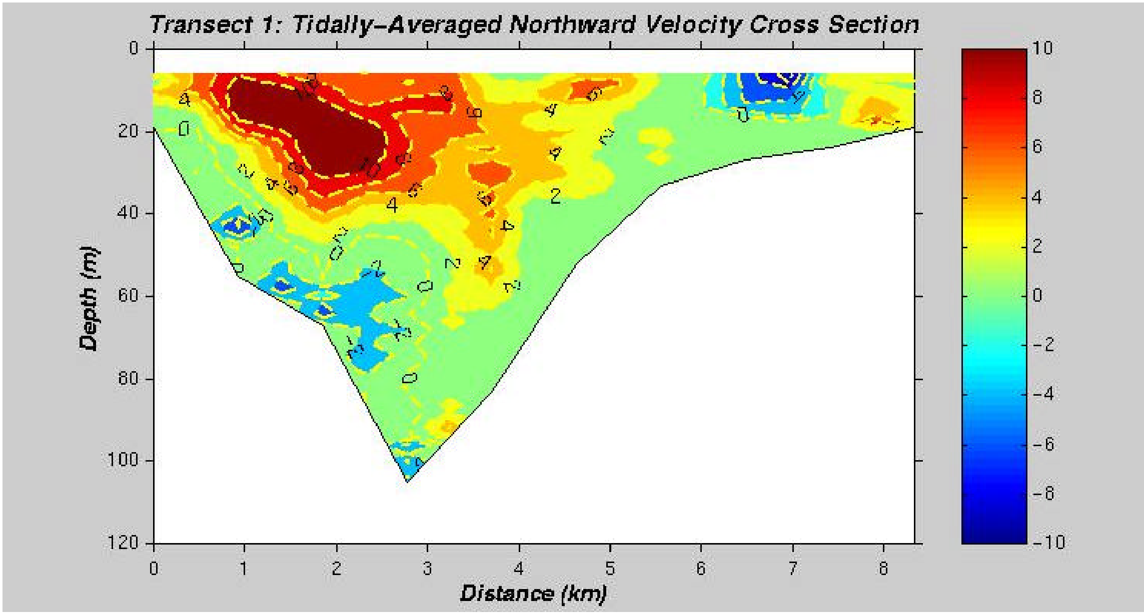


Figure 5.

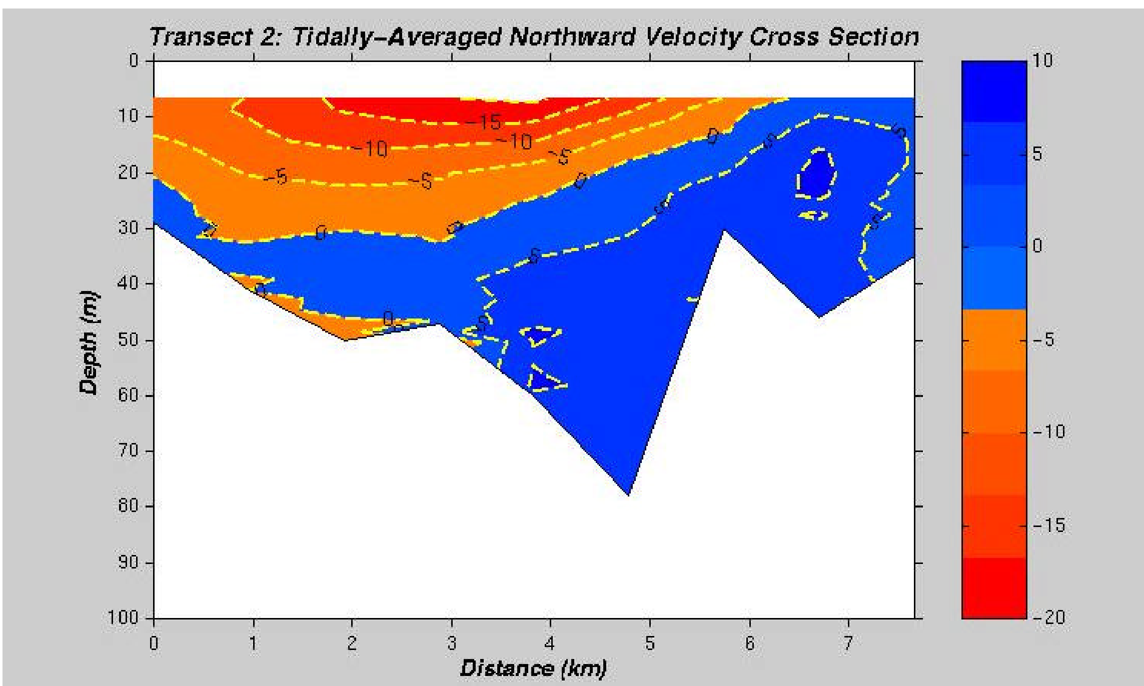


Figure 6.

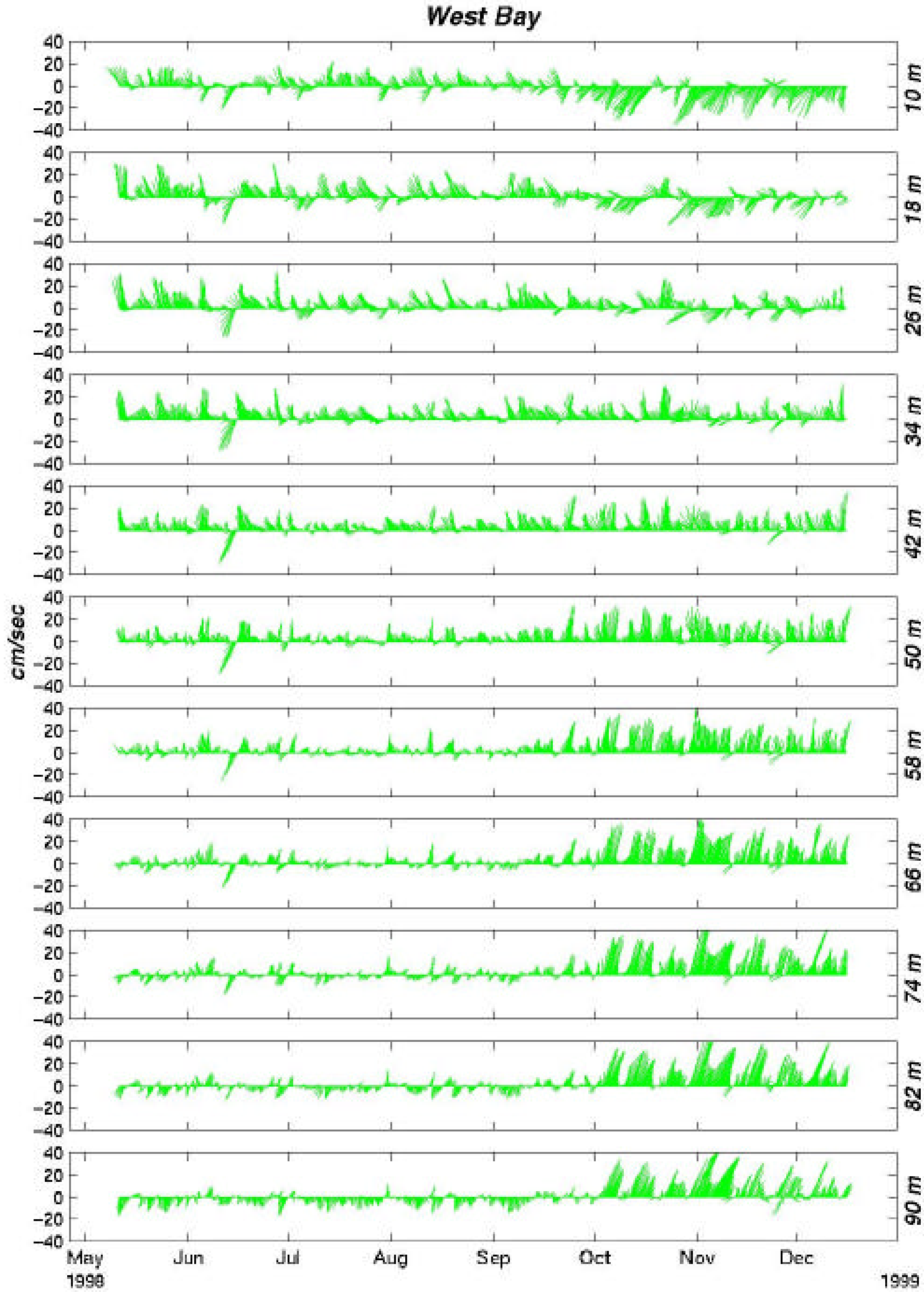

West Bay
cm/sec
10 m
18 m
26 m
34 m
42 m
50 m
58 m
66 m
74 m
82 m
90 m
May
1998
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1999

Figure 7.

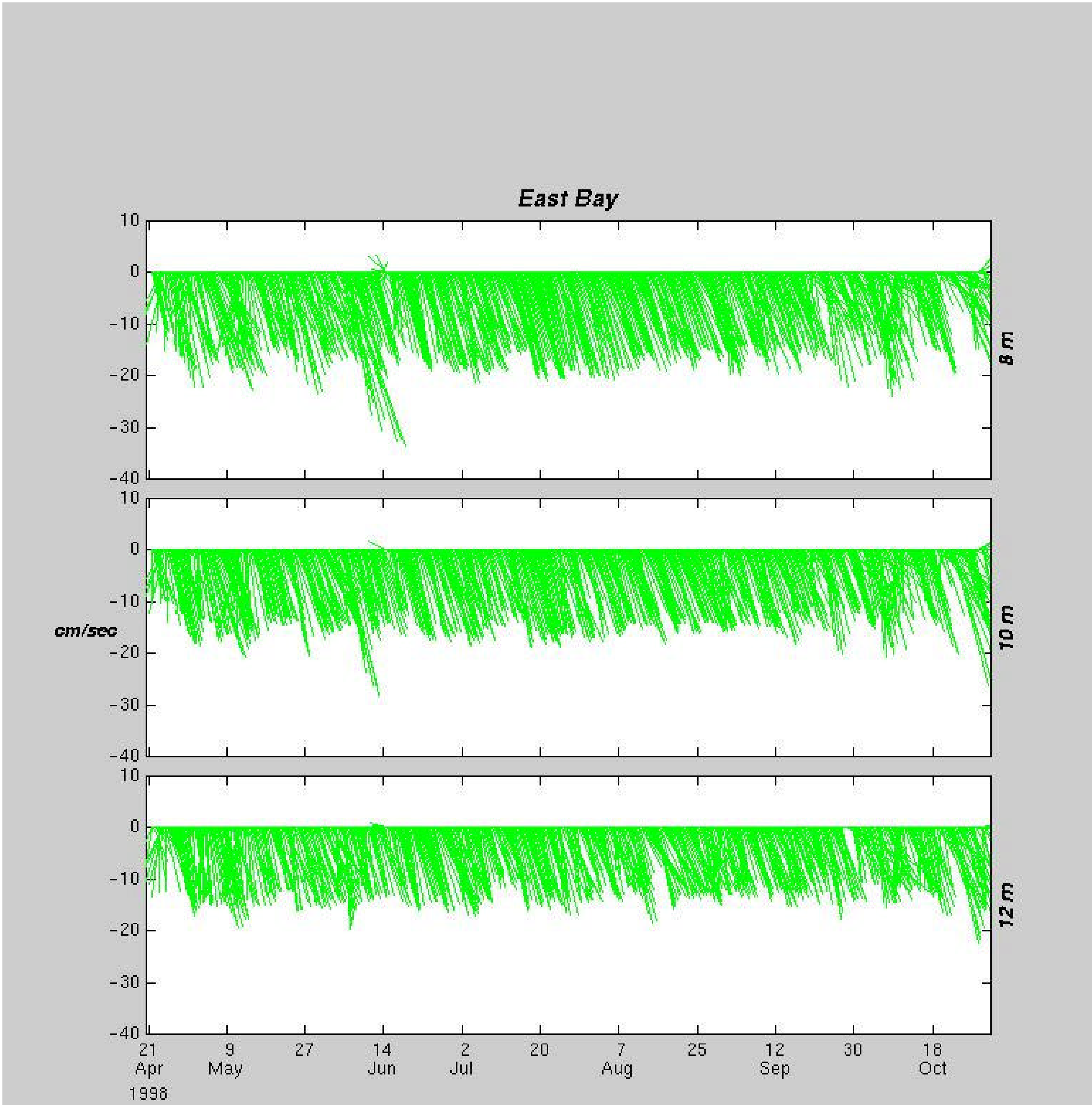
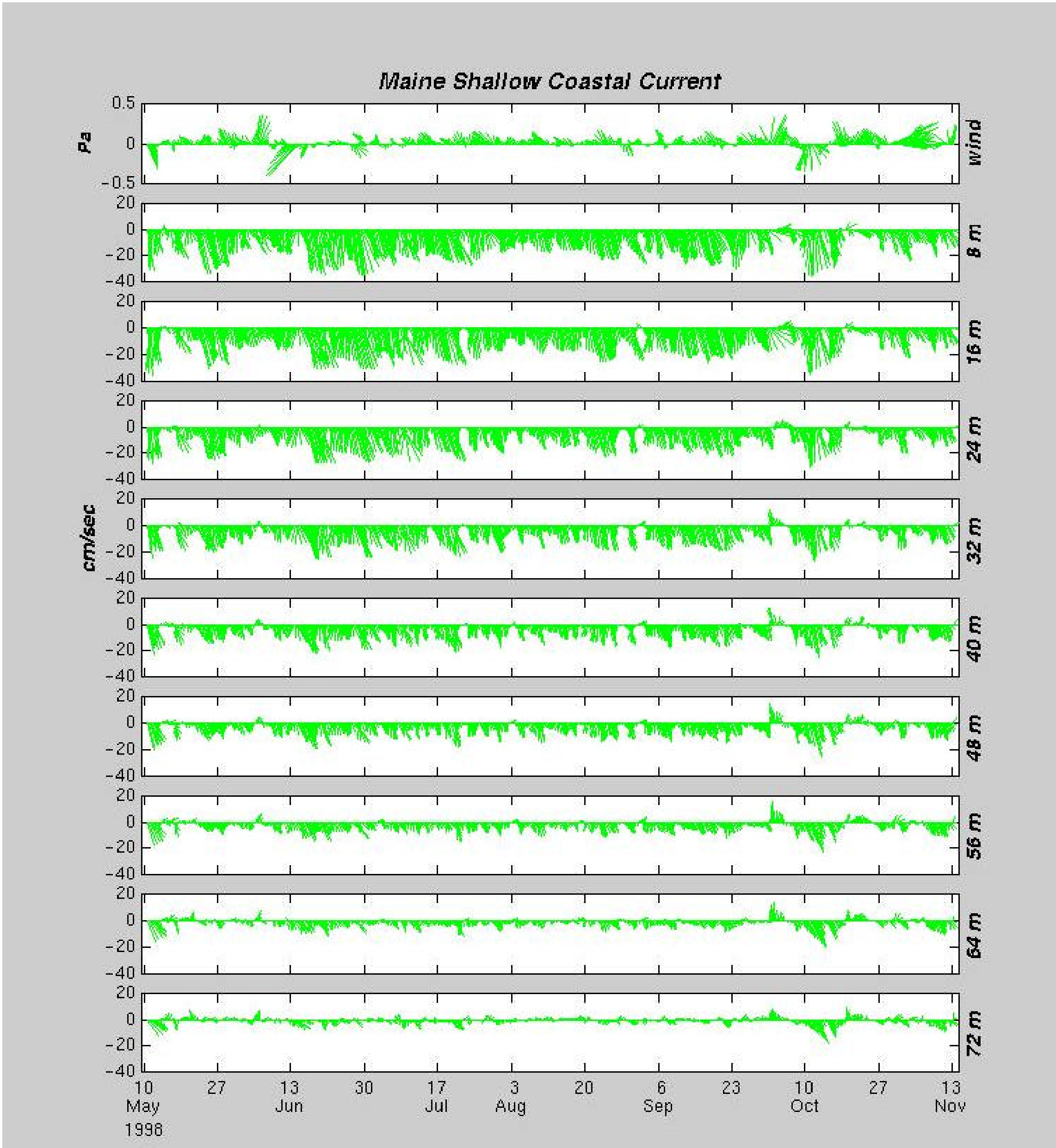

East Bay
cm/sec
8 m
10 m
12 m
10
0
-10
-20
-30
-40
21 Apr 1998
9 May
27
14 Jun
2 Jul
20
7 Aug
25
12 Sep
30
18 Oct

Figure 8.



Maine Shallow Coastal Current
Pa
wind
8 m
16 m
24 m
32 m
40 m
48 m
56 m
64 m
72 m
cm/sec
0.5
0
-0.5
20
0
-20
-40
10
May
1998
27
13
Jun
30
17
Jul
3
Aug
20
6
Sep
23
10
Oct
27
13
Nov

Figure 9.

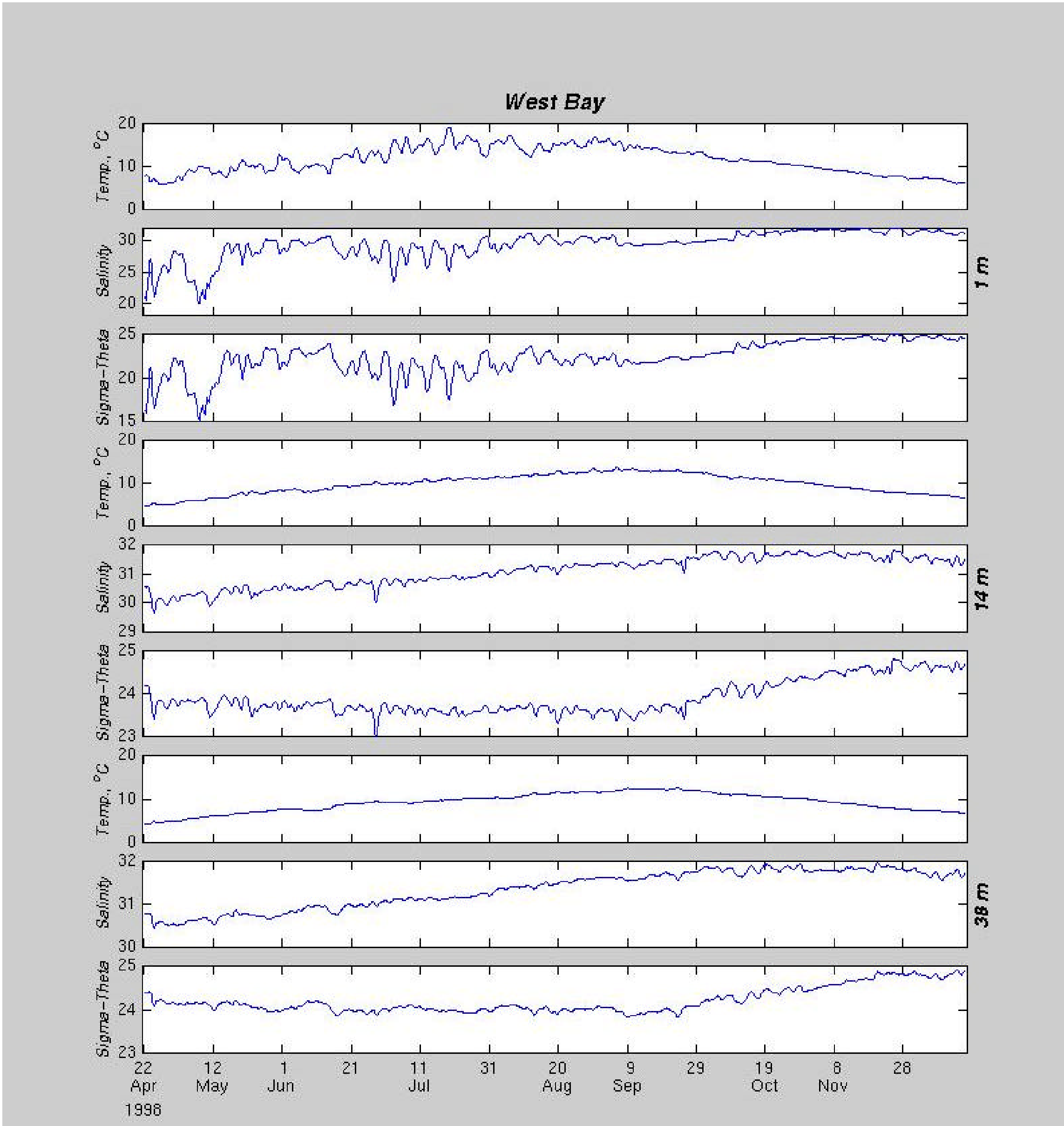

West Bay
Temp., °C
Salinity
Sigma-Theta
1 m
14 m
38 m
22
Apr
1998
12
May
1
Jun
21
11
Jul
31
20
Aug
9
Sep
29
19
Oct
8
Nov
28

Figure 10.

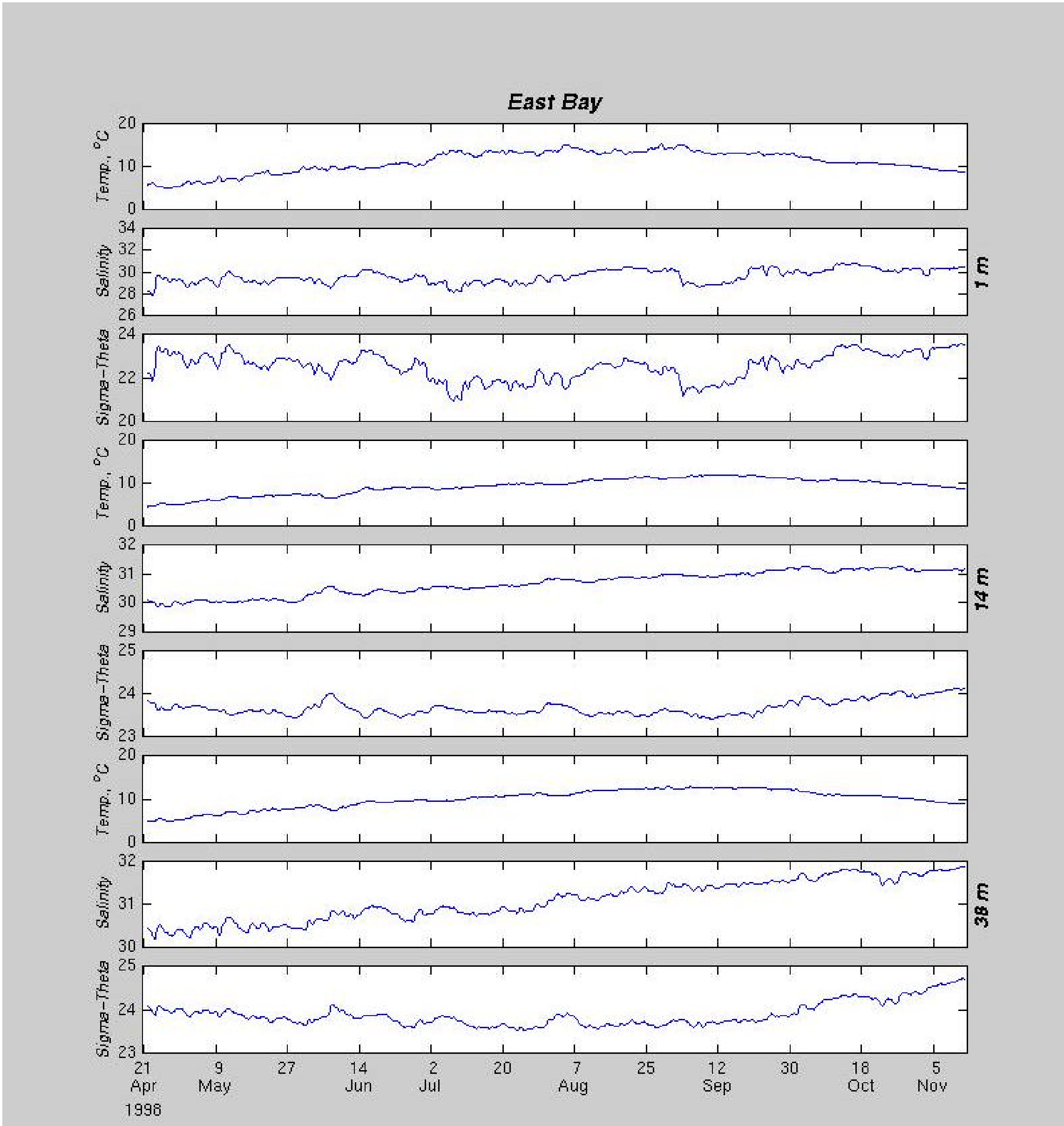

East Bay
Temp., °C
Salinity
Sigma-Theta
1 m
14 m
38 m
21 Apr 1998
9 May
27
14 Jun
2 Jul
20
7 Aug
25
12 Sep
30
18 Oct
5 Nov

Figure 11.